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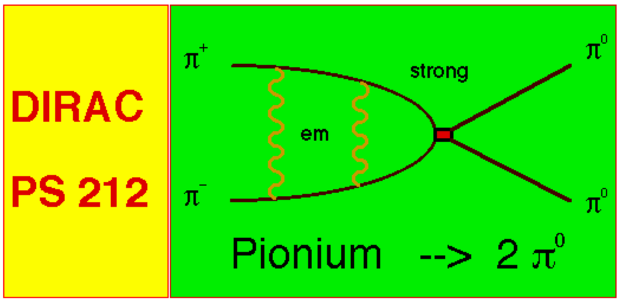

DIRAC Experiment at CERN: LIFETIME MEASUREMENT OF PIONIUM

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ABSTRACT

The DIRAC experiment, a magnetic double arm spectrometer, aims to measure the $\pi^+\pi^-$ atom lifetime with 10% precision, using the high intensity 24 GeV/c proton beam of the CERN Proton Synchrotron. Since the value of this lifetime of order 10^{-15} s is dictated by strong interaction at low energy, a precise measurement of this quantity enables to study characteristic pion parameters in detail and to submit predictions of QCD to a severe check.

INTRODUCTION. Pion scattering at low energies involves only the lightest observed hadrons and, therefore, is a key issue of low energy QCD. This pure process has been analysed in terms of scattering amplitudes and, hence, in terms of scattering lengths. By means of CHiral Perturbation Theory (CHPT) precise values for pion scattering lengths presumably at the 5% level are and will be predicted [1], experimentally not confirmed up to now (the best precision: $\sim$ 20% by Rosselet et al. [2]).

The Collaboration DIRAC (DImeson Relativistic Atom Complex, PS212 at CERN) intends to measure the ground-state lifetime of the atom "Pionium". Pionium or $A_{2\pi}$ is the Coulomb bound state, formed by π^+ and π^- mesons, with the following predicted properties:
1. Bohr radius: $r_B = 387$ fm
2. Coulomb energy of the ground state: $E(1\mathrm{S}) = -1.86$ keV
3. Ground-state quantum numbers: $J^{PC} = 0^{++}$
4. Pionium will decay in more than 99% of the cases by strong interaction into two neutral pions with a ground-state lifetime τ of about 3 fs.

The $\pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$ reaction or decay rate from the atomic ground-state must be given by characteristic pion parameters at low energy around threshold, i.e. at $E = 2m_\pi(1 - \alpha^2/8)$. As a well defined quantity in pion physics, the pionium lifetime should be known with good precision. Therefore, DIRAC aims to extract from data at least a 10% precise value for τ. In the case of using Deser-type relationships [3] between τ and s-wave scattering lengths (isoscalar minus isotensor) $\tau^{-1} = C \cdot \Delta^2$ with $\Delta = a_0 - a_2$, we envisage a determination of scattering (or decay) lengths (difference) down to few percent [4].

PRODUCTION, DETECTION AND LIFETIME MEASUREMENT OF $A_{2\pi}$. The method of pionium production, observation and lifetime measurement has been proposed many years ago by Nemenov, and details are described in reference [5]. Coulomb bound states or atoms can be produced in processes, where oppositely charged particles are emitted in the final state. Atoms, formed in this way, are in S-states. The corresponding cross section is proportional to the double inclusive production cross section σ_s^0 for $\pi^+\pi^-$ pairs from short-lived sources excluding Coulomb interaction in the final state and to the probability density function of pionium at the origin (with quantum numbers n and $l = 0$):

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \, \frac{E_A}{M_A} \, |\Psi_n(0)|^2 \, \left. \frac{d\sigma_s^0}{d\vec{p}_1 \, d\vec{p}_2} \right|_{\vec{p}_1 = \vec{p}_2 = \vec{p}_A/2} \tag{1}$$

where $\vec{p}_A$, E_A and M_A are momentum, energy and mass of the $\pi^+\pi^-$ atom in the laboratory system, respectively; $\vec{p}_1$ and $\vec{p}_2$ are the π^+ and π^- momenta in the laboratory system. The π^+ and π^- momenta obey the relation $\vec{p}_1 = \vec{p}_2 = \vec{p}_A/2$.

For the DIRAC experiment it is proposed to generate $A_{2\pi}$ atoms in 24 GeV/c proton - nucleus (e.g. Ti or Ni) collisions at the CERN PS. After production in a thin target of around 100 μm thickness, the relativistic ($\gamma \simeq 15$) atoms may either decay into $\pi^0\pi^0$ or get excited or broken up (ionized) in the material of the that target. In the case of breakup, a characteristic charged pion pair will appear. The so-called "atomic pair" will be observed by recording pions, which show a low relative momentum in their centre of mass system ($q < 3$ MeV/c). These pions have a small opening angle ($\theta_{+-} < 3$ mrad) and about the same laboratory energies ($E_+ \simeq E_-$ at the 0.3% level). Pions from $A_{2\pi}$ breakup will lead to an excess of events above a large background of $\pi^+\pi^-$ pairs from free states ("free pairs").

If the target thickness is of the order of the length for pionium interaction with target atoms, then the fraction of ionized pionia will be well measurable. The experimental setup, a magnetic double arm spectrometer, is designed to identify charged pions and to measure *relative pair momenta* q with high resolution of $\delta q \simeq 1$ MeV/c. By means of this precision apparatus the signal - the number of "atomic pairs" - can be separated from background - "free pairs" - and will be found in the following way: The number n_A of signal events is given by the difference between the full number of $\pi^+\pi^-$ pairs in the low momentum range ($q < 3$ MeV/c), in which most of the "atomic pairs" are expected to fall, and the computed number of "free pairs" in the same q interval. To extract that number from the data, the distribution of the momenta q for "free pairs" is fitted for $q > 3$ MeV/c by a function, based on the accidental pion pair distribution, and then extrapolated back to the signal region. The fit function takes into account $\pi^+\pi^-$ pair production from short-lived (e.g. ρ) as well as from long-lived (e.g. η_0) sources (for details see [4]). The total number N_A of generated $A_{2\pi}$ is obtained from the measured number of "free pairs" originating from short-lived sources for $q < 3$ MeV/c and by using formula (1). Thus the probability for $A_{2\pi}$ breakup can be defined as $P_{br}(\gamma \cdot \tau) = n_A(\gamma \cdot \tau)/N_A(\gamma)$. For a given target material and thickness, this ratio depends on the **pionium lifetime** τ. The function $P_{br}(\gamma \cdot \tau)$ is given by the interaction of pionium with the target atoms and is calculated with good precision. With help of this dependence the experimentally found breakup probability $P_{br}(exp)$ allows us to derive a value for the pionium lifetime.

SETUP, TRIGGER AND PIONIUM YIELD. The DIRAC setup (see figure) is going to be installed in the ZT8 beam area of the PS East Hall just now. Extracted from PS the 24 GeV/c proton beam is focused on the target (2 in figure). The ZT8 beam will be operated at an intensity of about $2 \cdot 10^{11}$ protons per spill of length 0.35 s with a cycle period of 14.4 s, corresponding to a 2.4% duty cycle. The secondary particle channel with a aperture of 1.2 msr is arranged at an angle of 5.7^0 to the primary proton beam and will detect pairs of $\pi^+\pi^-$ in the pion momentum interval $1 \div 6$ GeV/c.

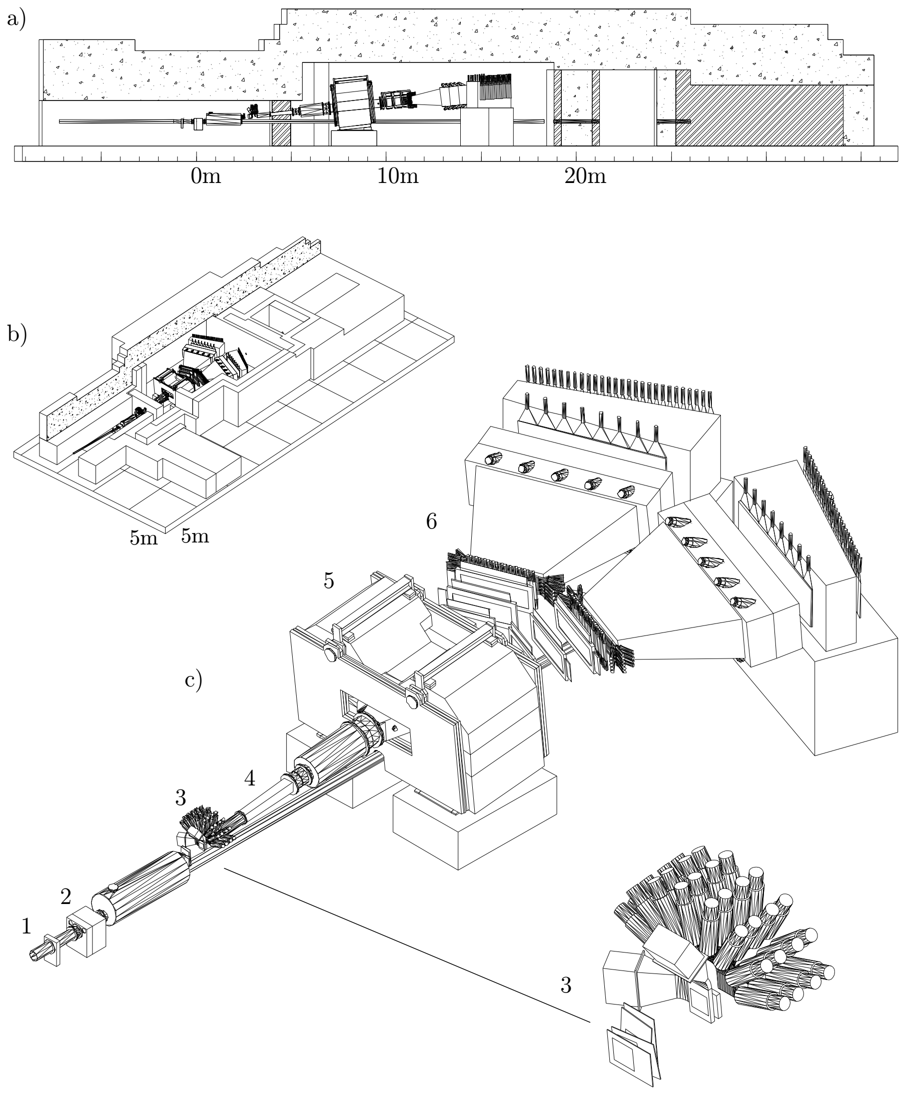
DIRAC [4] consists of the following components: Four micro-strip gas chambers, a set of scintillating fibre detectors and scintillation hodoscopes (3 in figure) near the target, a spectrometer magnet (5) of 2.3 Tm bending power and two telescope arms (6), each equipped with drift chambers, vertical and horizontal scintillation hodoscopes, gas Cherenkov counters, preshower detectors and muon identifiers. The relative momentum resolution required for identification of "atomic pairs" is provided by the high coordinate resolution of the fibre detector, micro-strip gas chambers and the drift chambers. In order to reject electrons and muons, the system of threshold Cherenkov counters, operated with Nitrogen, preshower detectors and muon scintillation counters is being installed in each arm. For suppressing the large background rate a multilevel trigger logic is used. Besides a fast zero level trigger - a 2-arm coincidence $(VH \cdot Pr)_1 \cdot (VH \cdot Pr)_2$ of vertical hodoscopes VH and preshower detectors Pr - the first level trigger is provided by a coincidence between the following responses of the two telescope arms:

$$(VH \cdot HH \cdot \overline{C} \cdot \overline{S_\mu})_1 \cdot (VH \cdot HH \cdot \overline{C} \cdot \overline{S_\mu})_2$$

where VH and HH mean the vertical and horizontal scintillation hodoscopes, C the Cherenkov counters and S_μ the muon counters. At the higher levels the response of detectors upstream of the magnet is included. Special processors investigate the event topology on the basis of the pair opening angle (SFD) and the (double) ionization loss in the forward scintillation hodoscopes (FSD). The topological criterion is aimed to select events with low relative momentum of the detected particle pair. By these means the average rate of events recorded on tape is estimated to be around 30/s. To achieve the goal of DIRAC - a measurement of the $A_{2\pi}$ lifetime with 10% precision - we have to consider a running time of at least 5 weeks (per target), corresponding to $\sim$ 20000 recorded "atomic pairs". Of course additional data will be taken for tests, calibration and runs with different target materials.

CONCLUSION. From the experimental point of view, it is a challenge to produce in a high energy collision atomic states, in our case $\pi^+\pi^-$ atoms, and to measure their lifetime, which is of the order 10^{-15} s.

From the theoretical point of view, it is also a challenge to understand reliably the dependence of the $A_{2\pi}$ lifetime from characteristic pion parameters like scattering (decay) lengths and then to extract precise values for these quantities.



DIRAC Experimental setup: a), b) — setup inside the radiation shielding; c) — isometric projection: 1 — proton beam tube; 2 — target station; 3 — detectors upstream of the magnet: microstrip gas chambers, scintillating fibre detectors, scintillation ionization hodoscopes; 4 — secondary particle channel; 5 — spectrometer magnet; 6 — detectors downstream of the magnet: drift chambers, vertical and horizontal scintillation hodoscopes, gas Cherenkov counters, preshower detectors, muon scintillation counters.

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